Aerodynamic Configuration Analysis of a Typical Inflatable Aerodynamic Decelerator

N. Uday Bhaskar, B. Deependran and V. Ashok

Abstract A fore-body attached inflatable ballutes were considered for the aerodynamic analysis. Detailed CFD studies for sensitivity of aerodynamic coefficients to cone angle, varying payload length and center of gravity location were carried out. Flow simulations carried out for multiple angles of attack (AoA) at different altitude conditions. Variation of aerodynamic coefficients, i.e., axial force coefficient, normal force coefficient and pitching moment coefficient with angle of attack at multiple altitudes and free stream conditions is reported. Analysis for tumbling cases was carried out at higher altitudes. Aerodynamically, an IAD configuration, which is more stable and with maximum drag, i.e., with minimum ballistic coefficient is considered ideal. Based on the parametric studies, an optimum configuration was arrived, which was statically stable with ($\mathrm{d}C_m/\mathrm{d}\alpha$) at 0° of −0.18 and a ballistic coefficient of 4.6 which meets the mission requirements. Variation of pitching moment coefficient about stagnation point with angle of attack clearly indicates that IAD configuration is statically stable to 60° AoA.

Keywords Inflatable aerodynamic decelerator · Ballistic coefficient · Static stability · Pitching moment coefficient · Cone included angle · Payload length and center of gravity location

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1 Introduction

Inflatable aerodynamic decelerators (IAD) have distinct advantage over conventional rigid aeroshell counterparts in several respects: increased payload mass and volume fraction and provide a more benign payload thermal environment during entry as a result of very low ballistic coefficient [1]. Keeping the above-mentioned objectives in mind, the potential benefits of flexible decelerators for aero-capture must be tapped especially for interplanetary missions. Multiple configurations like trailing ballute, after-body attached ballute, fore-body attached inflatable aeroshell, etc., in the family of aero-capture inflatable decelerators are discussed in [2], which provide a brief overview of different configurations and associated design concepts of IAD considered across the world. Aerodynamically, an IAD configuration which is more stable and with maximum drag, i.e., low ballistic coefficient is considered ideal.

In the present analysis, detailed CFD studies for sensitivity of aerodynamic coefficients to different geometric parameters were carried out for a fore-body attached inflatable ballutes configuration shown in Fig. 1.

2 Grid Generation and Analysis Conditions

Structured 3D, body-fitted multi-block grids were generated using algebraic methods shown in Fig. 2, cut section of the grid with a million cells used for forward-facing flow cases is shown in Fig. 2a, and grid shown in Fig. 2b with further stretched far-field boundary with 1.4 million cells is generated for the analysis of flow AoA beyond 70° corresponding to the tumbling of IAD at higher altitudes. Two different views of surface grid representing IAD body are shown in Fig. 2c.

Viscous, compressible flow simulations were carried out using CFD++ solver of Metacomp Technologies [3], for multiple angles of attack (AoA) at different altitude conditions reported in [1]. Variation of aerodynamic coefficients with angle of attack at multiple altitudes and free stream conditions as listed in Table 1 are reported. Analysis for tumbling cases was carried out at higher altitudes.

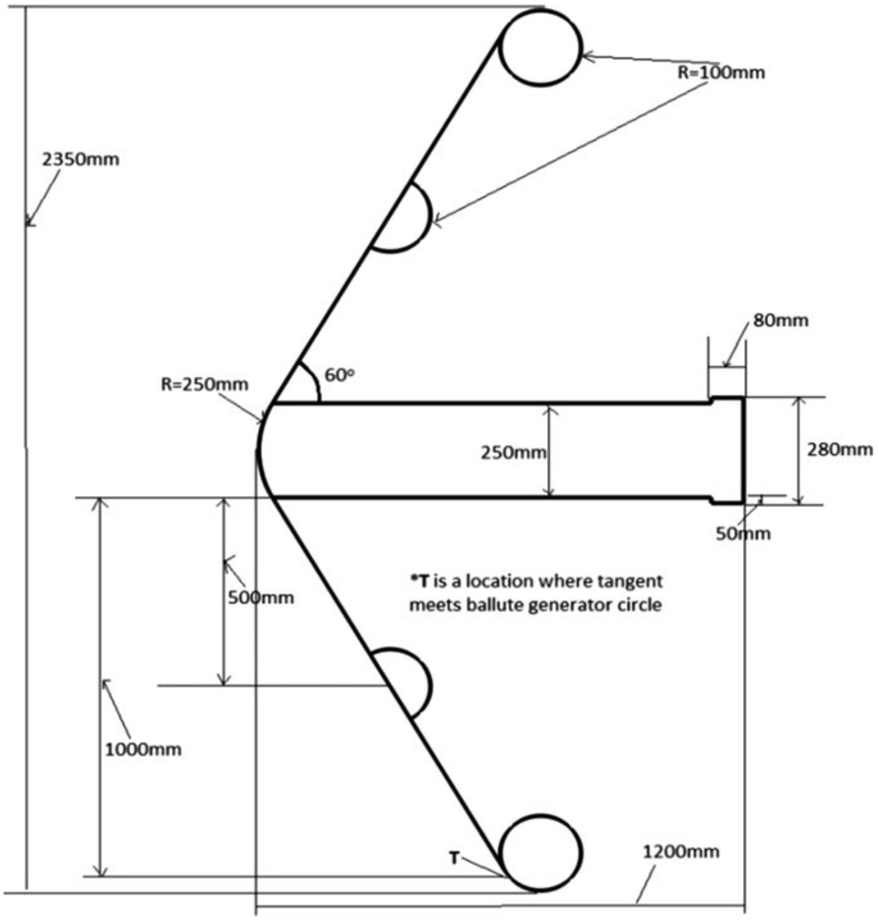
R=100mm
2350mm
80mm
60°
R=250mm
250mm
280mm
50mm
500mm
*T is a location where tangent meets ballute generator circle
1000mm
T
1200mm

Fig. 1 Geometric configuration of IAD considered for analysis

3 CFD Analysis for Validation Studies

For validation studies, initial computational analysis was carried out by regenerating the flow field around IRVE using in-house tools for the geometry and flow conditions reported in [1]. Figure 3a shows the surface grid for geometric configuration of IRVE regenerated, and Fig. 3b shows the temperature palette of the flow field around it, which is similar to that reported in Fig. 8 of [1]. With the confidence developed after re-generation of IRVE flow field using in-house tools, flow analysis carried out for the present IAD configuration.

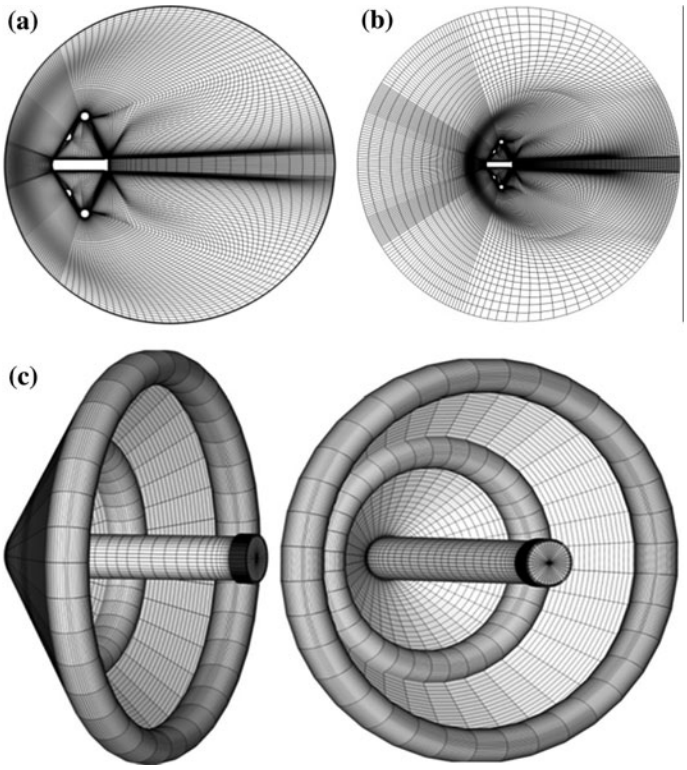

Fig. 2 Grid, **a** used for the forward-facing flow analysis, **b** used for tumbling cases, **c** surface grid of IAD

Table 1 Altitude, free stream velocities and AoA analysis matrix considered for analysis

Altitude (km)	Velocity (m/s)	Angles of attack (deg)
46	831.0	0°, 5°, 15°, 30°, 45°, 60° and 70°
56	1245.0	0°, 5°, 15°, 30°, 45°, 60° and 70°
65	1349.0	0°, 5°, 15°, 30°, 45°, 60° and 70°
75	1337.0	0°, 5°, 15°, 30°, 45°, 60° and 70°
85	1276.0	0°, 5°, 15°, 30°, 45°, 60°, 70°, 90°, 135°, 165° and 180°
95	1205.0	0°, 5°, 15°, 30°, 90°, 135°, 165° and 180°
100	1159.0	90°, 135°, 165° and 180°

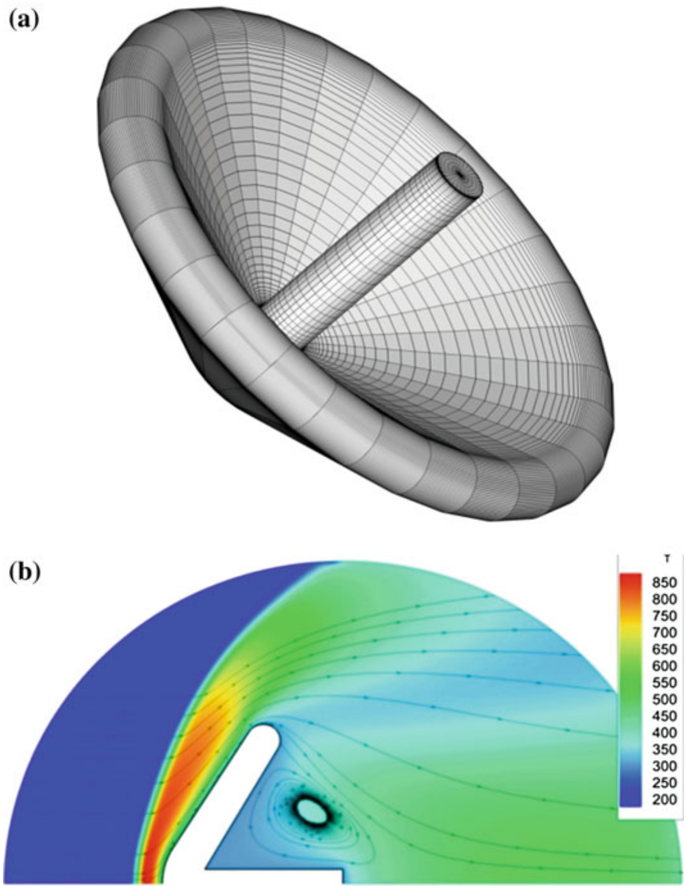

Fig. 3 Regenerated, **a** surface grid for IRVE configuration, **b** temperature palette of the flow field

4 Sensitivity Analysis

CFD studies for sensitivity of multiple configuration parameters such as cone angle, payload length and center of gravity location on aerodynamic coefficients were carried out.

4.1 Cone Angle

Analysis was carried out for three different included cone angles for the same geometric configuration by just varying the cone included angles as shown in Fig. 4.

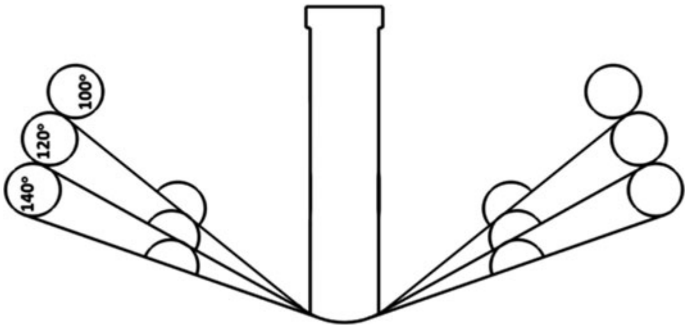

Fig. 4 Configurations considered for sensitivity of cone angle

Configuration which is more stable and with maximum drag (low ballistic coefficient) is considered ideal. From plots of variation of pitching moment with AoA shown in Fig. 5a, b at different altitudes for all three cone angles, it is clearly observed that cone with 100° included angle is more stable with maximum. $|dC_m/d\alpha|$ and from plots of variation of drag coefficient with Angle of attack (AoA) shown in Fig. 6a, b at different altitudes for all three cone angles, Cone with 140° included angle has the maximum drag coefficient.

Configuration with 120° cone angle can be considered comparatively as optimum configuration with almost same drag coefficient as that of 140° cone with higher static stability.

4.2 Payload Length

In general, any aerospace-related missions have a tight budget in terms of payload mass and volume. In order to study how sensitive is the length of payload on aerodynamic coefficients, CFD analysis for three different payload lengths was carried out by keeping the cone angle at 120°. Configurations with different payload lengths considered for analysis are shown in Fig. 7.

Figure 8a, b show the variation of pitching moment coefficient with AoA about stagnation point at different altitudes for all three payload lengths, as it can be observed that pitching moment coefficient is insensitive to payload length at least for the considered payload lengths. Hence, it is concluded that configuration with maximum payload length, i.e., 1.2 m can be considered to be optimum as more volume would be available.

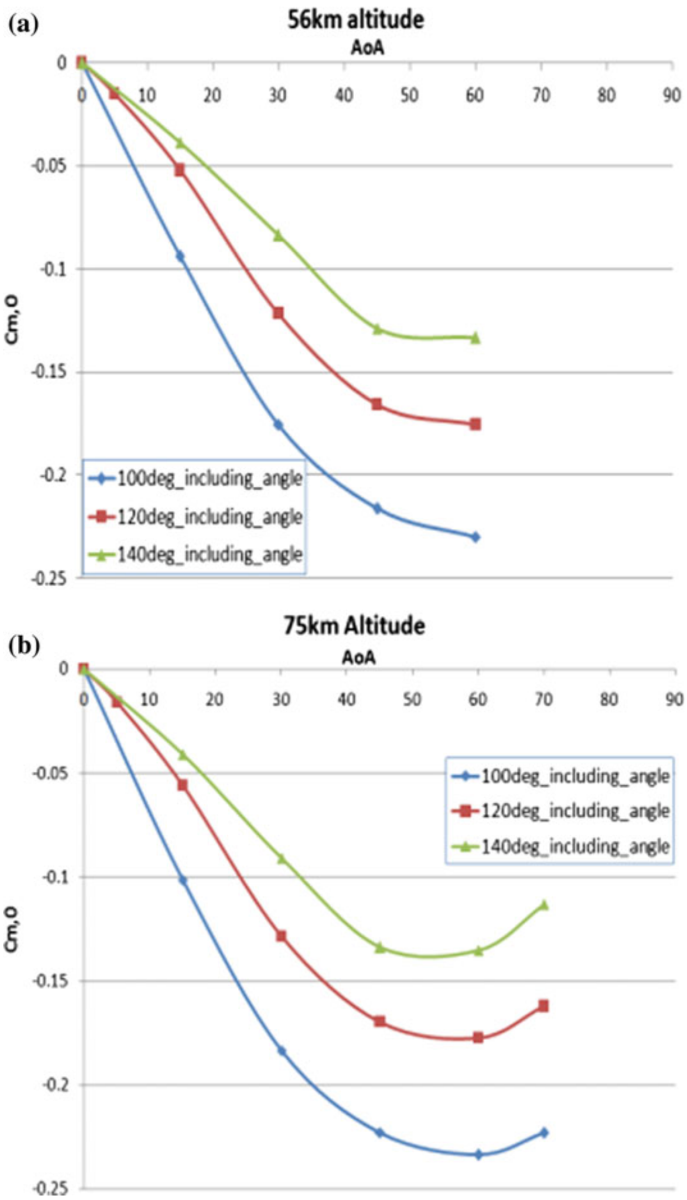

Fig. 5 Variation of pitching moment coefficient about stagnation point with AoA for different cone angles at **a** 56 km altitude and **b** 75 km altitude

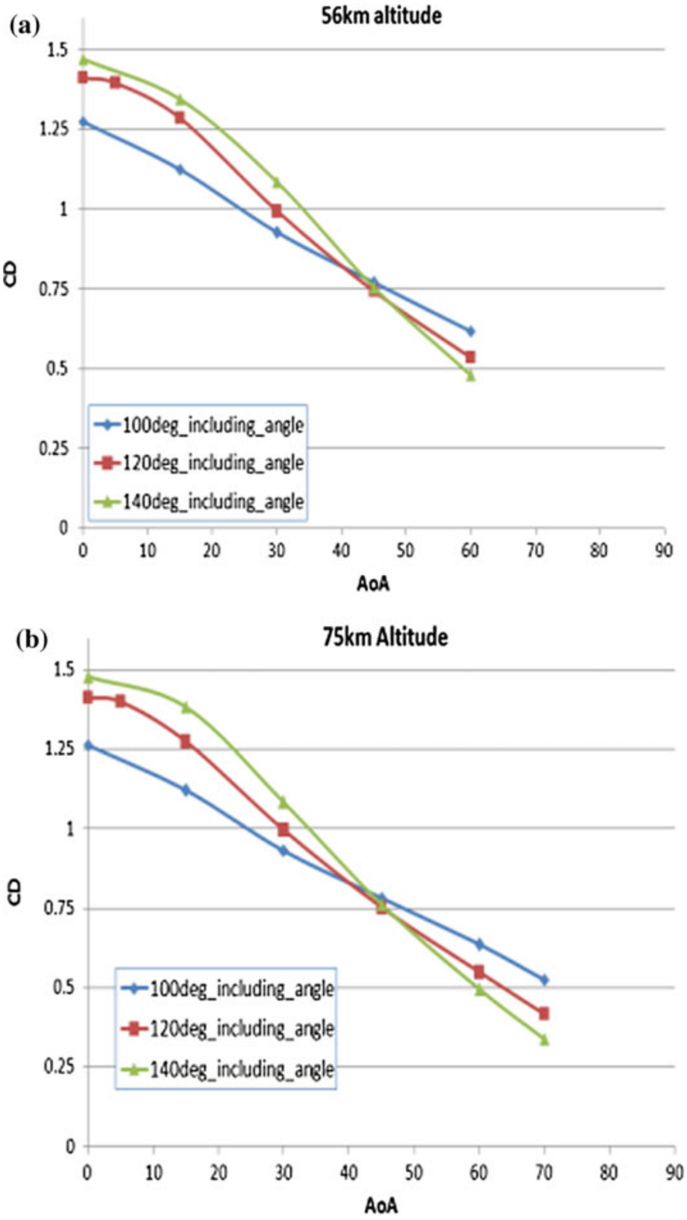

Fig. 6 Variation of drag coefficient with AoA for different cone angles at **a** 56 km altitude and **b** 75 km altitude

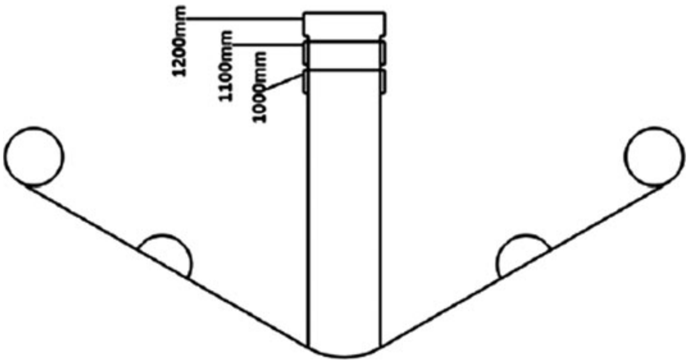

Fig. 7 Configurations considered for sensitivity of payload length

4.3 Center of Gravity Location

For a typical aerospace configuration, center of gravity location is a very important input parameter in the very beginning of design and sizing phase, which decides the stability margins. Based on the optimal center of gravity (CG) location required for the mission, weights can be packed/distributed accordingly in the cylindrical console.

To analyze the sensitivity of aerodynamic coefficients to CG location, pitching moment coefficients about different CG locations from stagnation point as shown in Fig. 9 were computed for the configuration with 120° cone angle and a payload length on 1.2 m.

Variation of pitching moment with AoA with respect to different CG locations is shown in Fig. 10a–c. With respect to distance of center of gravity from stagnation point, configuration for which CG is closest to stagnation point is more stable, i.e., with CG location at 0.45 m from stagnation point. While considering the packing/distributing the different components (masses) in the payload cylinder, this conclusion can be kept in mind.

In conclusion from the sensitivity analysis of the IAD configuration carried out by varying the above-mentioned parameters, a configuration with 120° cone angle, payload length of 1.2 m and with center of gravity located nearest possible to stagnation point can be considered to be optimal.

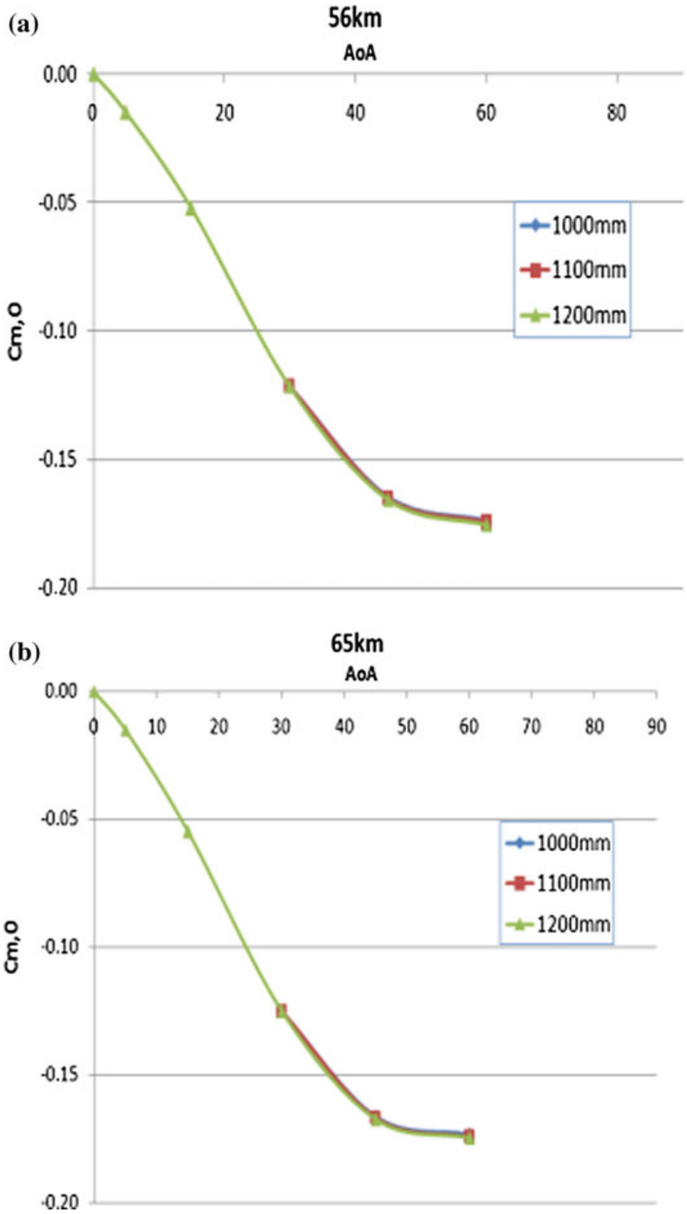

Fig. 8 Variation of pitching moment coefficient with AoA about stagnation point for different payload lengths at **a** 56 km altitude and **b** 65 km altitude

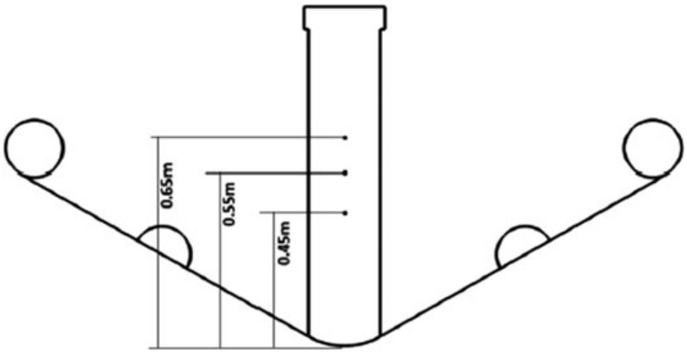

Fig. 9 Configurations considered for sensitivity of CG location

5 Computational Aerodynamic Analysis of the Inflatable Aerodynamic Decelerator

Detailed CFD analysis of the IAD with optimal geometric configuration from Sect. 4 above is carried out with the geometric configuration mentioned in Fig. 1, and altitudes, free stream velocities and angles of attack listed in Table 1. Iso-Mach number lines and palette in Fig. 11a, b show typical flow features like bow shock, re-circulation region, wake and re-compression shocks in downstream in the flow field around the IAD.

Axial force coefficient (CA) variation with respect to AoA is shown in Fig. 12 at different altitude conditions. At 0° and 180° angles of attack, CA is equal to drag coefficient. Maximum drag coefficient is observed to be about 2.0 for tumbling case of 180° at 100 km altitude case, whereas for forward-facing flow, maximum drag coefficient was consistently about 1.5 for all altitude cases at 0° angle of attack.

Variation of normal force coefficient with angle of attack for different altitudes is shown in Fig. 13.

Variation of pitching moment coefficient of the IAD with angle of attack about front stagnation point is shown in Fig. 14. It can be observed from the plot that the present configuration is statically stable up to 60° AoA for all the altitude cases considered.

Isometric 3D flow field view of plane Mach number palette at 135° and 180° angles of attack at 85 km altitude condition, i.e., tumbling cases can be seen from Fig. 15a, b.

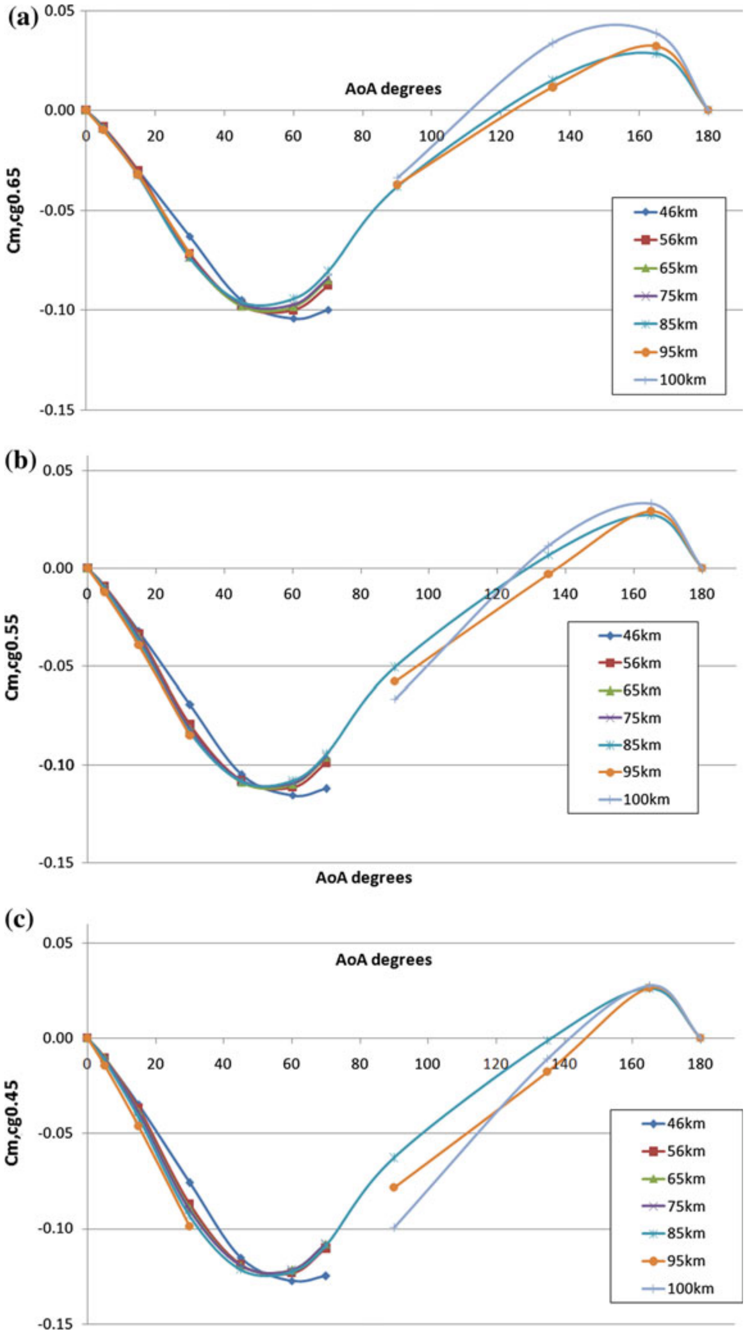

Fig. 10 Variation of pitching moment coefficient with AoA about different CG locations at **a** 0.65 m, **b** 0.55 m and **c** 0.45 m from stagnation point

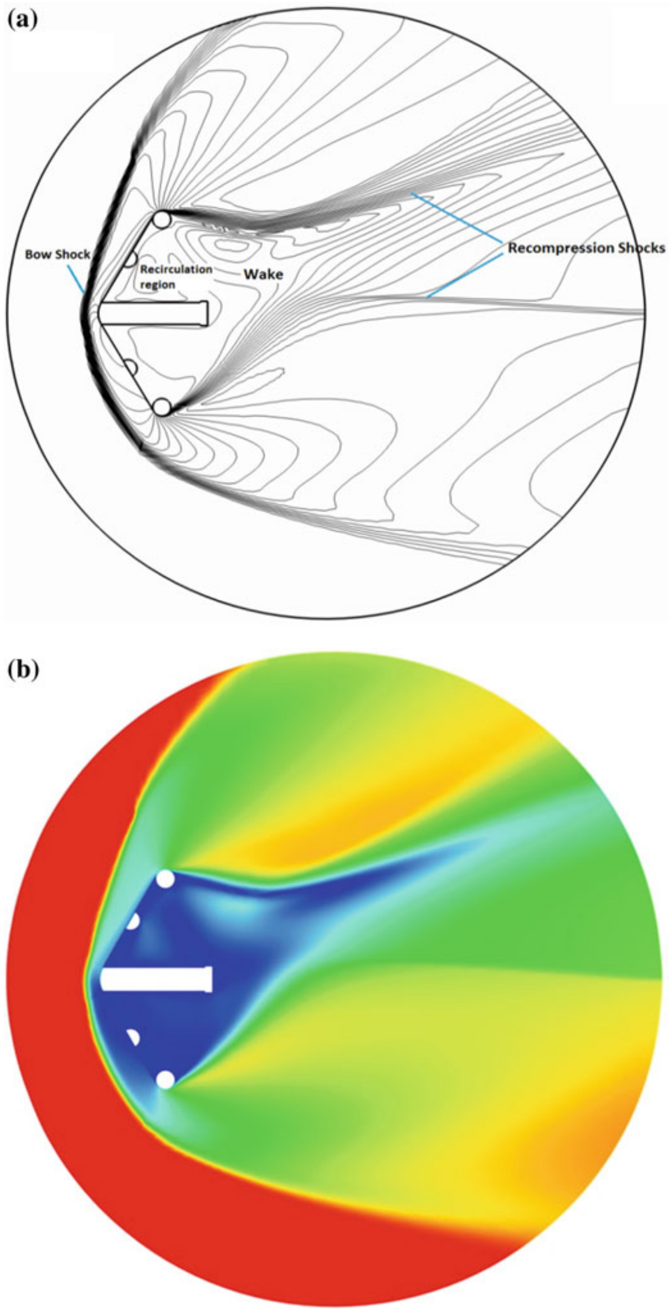

Fig. 11 Typical flow features around IAD at 65 km altitude conditions from **a** Iso-Mach lines and **b** Mach number palette

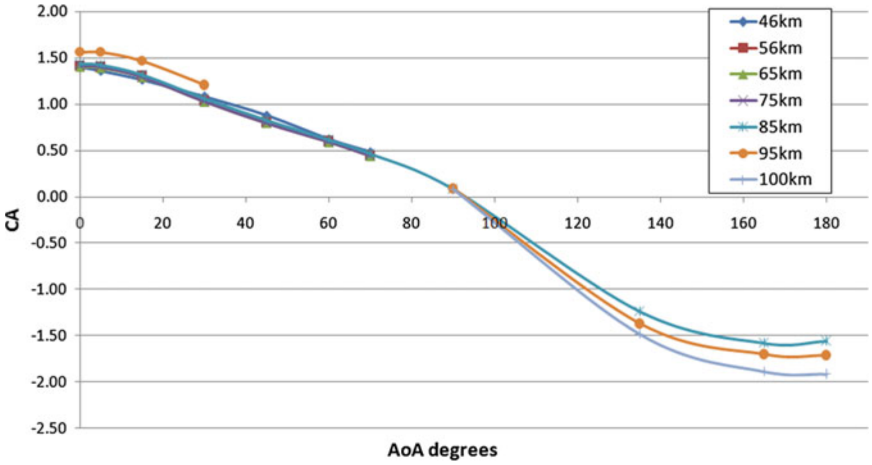

Fig. 12 Variation of axial force coefficient with AoA on IAD configuration at different altitude conditions

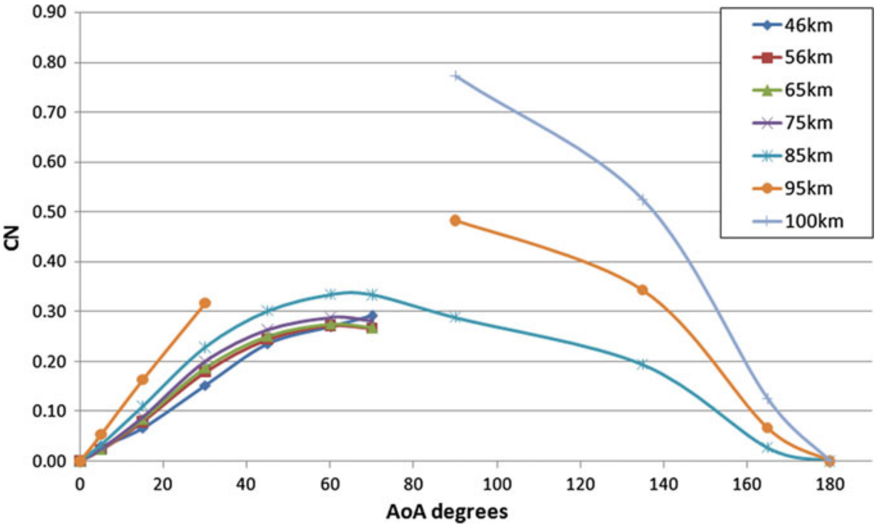

Fig. 13 Variation of normal force coefficient with AoA on IAD configuration at different altitude conditions

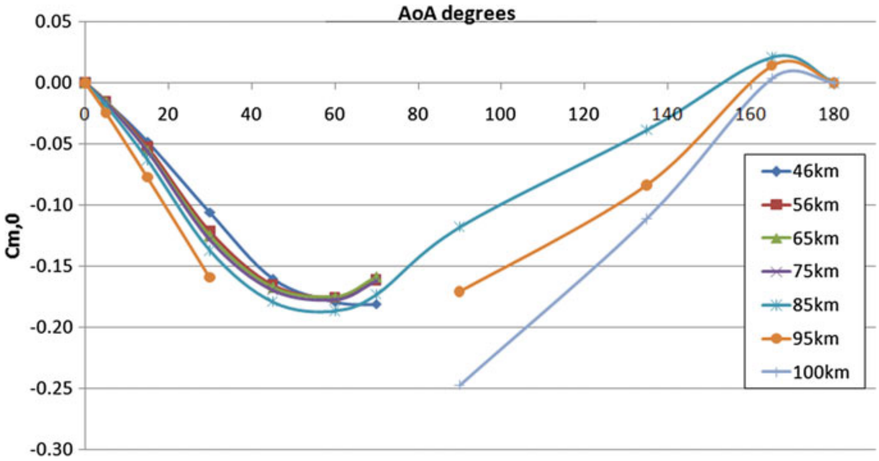

Fig. 14 Variation of pitching moment coefficient with AoA on IAD configuration at different altitude conditions

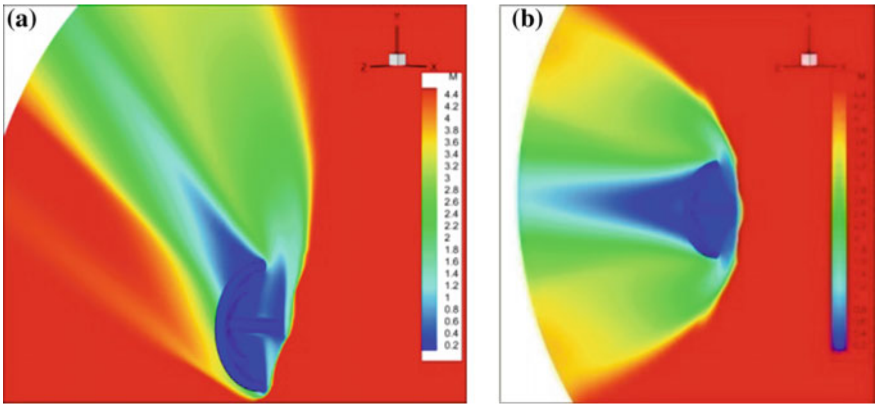

Fig. 15 Isometric 3D view of Mach number palettes of IAD at 85 km altitude conditions **a** at 135° AoA and **b** at 180° AoA

6 Conclusions

Aerodynamic configuration analysis of a typical inflatable aerodynamic decelerator (IAD) with fore-body attached inflatable ballute configuration was carried out. Analysis was carried out for tumbling cases too at higher altitudes.

Sensitivity of aerodynamic coefficients to cone included angle, payload length and center of gravity location was studied. From detailed CFD analysis the optimal configuration was selected based on the sensitivity studies of the parameters carried out. The configuration selected is statically stable with ($dC_m/d\alpha$) of −0.18 at 0° and ballistic coefficient was found to be approximately 4.6 kg/m^2 with C_D of 1.5, frontal area of 4.34 m^2 and by assuming the mass of IAD to be 30 kg.

Aerodynamic data generated from the present CFD analysis can be utilized for preliminary trajectory estimation. The data may be supplied in the form of tables of aerodynamic coefficients as a function of Mach number and altitude.

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